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Experimental techniques for charged particle spectroscopy

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Abstract : In heavy ion reactions, the singles spectra are quite complicated due to the existence of many exit channels. Identification and quantification of isotopic composition in outgoing channels is required for understanding of reaction mechanism. ΔE–E telescope provides a tool to separate particles of different Z and therefore energy spectra of different outgoing particles can be extracted. However the telescope is not suitable to separate out different isotopes of the species above $Z = 5$. Time of flight (TOF) with the telescope enables one to identify both Z and M. TOF technique and pulse shape analysis are useful in n–γ discrimination for neutron detection also. TOF can be carried out with pulsed ion beam or DC beam.

In this talk, various aspects of particle identification with telescope along with TOF technique, kinematic coincidence and n–γ discrimination will be discussed with suitable examples.

Keyword : Heavy ion reaction, charged particle spectroscopy

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1. Introduction

The interest in heavy ion physics picked up when heavy ion accelerators became available in the seventies. The interest was mainly due to the fact that (i) high energy heavy ions were able to transfer large angular momentum and large excitation energy in reactions, (ii) classical and semi-classical approaches could be applied to heavy ion reactions. Above the Coulomb barrier, the observed experimental spectra become more and more complicated due to the opening up of more and more exit channels because of available large excitation energy. The complicated energy spectra arise from overlapping energies of various reaction products. The identification and quantification of various particles and isotopic products in the exit channels is the key objective of experimentalists to understand the reaction mechanism and nuclear structure. This need leads to refinement and

development in nuclear techniques and detector technology. The solid state surface barrier detectors which were widely used in the experiments were prone to radiation damage. They undergo fast degradation of resolution with heavy ions. These detectors have pulse height defect for heavy ions which result in inaccurate energy measurement. Therefore lot of developments took place in gaseous ionization chambers as detectors and they became quite popular as they were not prone to radiation damage and their resolution do not deteriorate with heavy ions. Some interesting reviews on various nuclear detector developments are given by Stelzer [1], England [2], Goulding and Harvey [3], Martin and Stelzer [4] and Braid [5].

The identification of the ions produced in reactions is normally done in two ways. (1) The ion passing through a detector or a set of detectors produces ionization signal (due to collection of electrons and holes at the electrodes). The amplitude of the signal and its time information is exploited for particle identification. (2) The detection of ion is made after its traversal through a magnetic field, which is done in magnetic spectrometer. A nice review on magnetic spectrographs is given by Enge [6]. Different masses despite their overlapping energies follow different paths in magnet and get focussed at different points in focal plane.

In the present talk I shall be confining on the first method which focuses on the understanding of ΔE–E telescope, gaseous ΔE detector, time of flight (TOF) technique, different fast timing detectors, n–γ discrimination and pulse shape analysis for neutron detection.

2. Z identification by ΔE–E telescope

When an ion is stopped in detector material, the integrated ionization is proportional to the absorbed energy. The energy loss mechanism is mainly due to Coulomb interaction (between the ion and electrons of detector material) which causes production of positive and negative charges. These charges are collected by electrodes to produce a signal which is amplified by low noise electronics. The rate of energy loss of ion in a material is given by the well known Bethe-Bloch equation [7]

$$\frac{dE}{dx} = -4\pi n\left(\frac{e^4}{m}\right)\left(\frac{q_{eff}}{v^2}\right)\ln\left[2mv^2/I(1-\beta^2) - \beta^2 - S - D\right]. \tag{1}$$

For light ions, $q_{eff} = Z$ therefore the Bethe-Bloch equation can be written as

$$\frac{dE}{dx} = -AZ^2\left(C^2/v^2\right)\ln\left[Bv^2/(C^2 - v^2)\right] \tag{2}$$

where A and B are constants.

Since the logarithmic term varies slowly with energy, further simplified equation is

$$\frac{dE}{dx} \propto MZ^2/E. \tag{3}$$

Relation (3) deviates from the actual curve of (1) due to the logarithmic term. At low energies, incomplete stripping of ion violates the assumption of $q_{eff} = Z$ and therefore it causes the deviation of (3) from the actual case. At higher energies, the deviation appears due to relativistic effects. At even higher energies the dE/dx becomes proportional to Z^2.

As can be seen from expression (3), the amount of energy dE lost by the ions with different Z in a given thickness dx of stopping material is proportional to MZ^2. It becomes a basis to separate the ions of different species by using a transmission type thin E detector and a thick detector. The ion looses part of its energy in first ΔE detector and the rest of energy E is deposited in the second detector. Transmission type ΔE detector provides the information on MZ^2 and hence enables identification of the ion species. The sum of ΔE and E signals from two detectors provide total energy. It is however noticed that the isotopic separation for ions above $Z = 5$ is ambiguous due to overlapping values of MZ^2. For example $Z = 5$, $M = 13$ and $Z = 6$, $M = 9$ give MZ^2 value of 325 and 324, respectively. Other than this, MZ^2 signal-spread due to spread in ΔE and E signals becomes a major limitation in ion identification. It may arise because of (i) pulse height defect, (ii) variation in thickness of ΔE detector as well as in dead layers of the detectors, (iii) fluctuation in charge state of ion passing through ΔE detector, (iv) nuclear collision at the end of track in E detector which do not provide ionization signal.

2.1. Gaseous ionization chamber as ΔE detector

Thickness of the surface barrier detector to be used for ΔE transmission type detector depends on the mass and energy of the ion to be detected. It should be such that the ion of interest deposits at least 10% to 20% (ideally 50%) of its total energy. Heavy ions typically

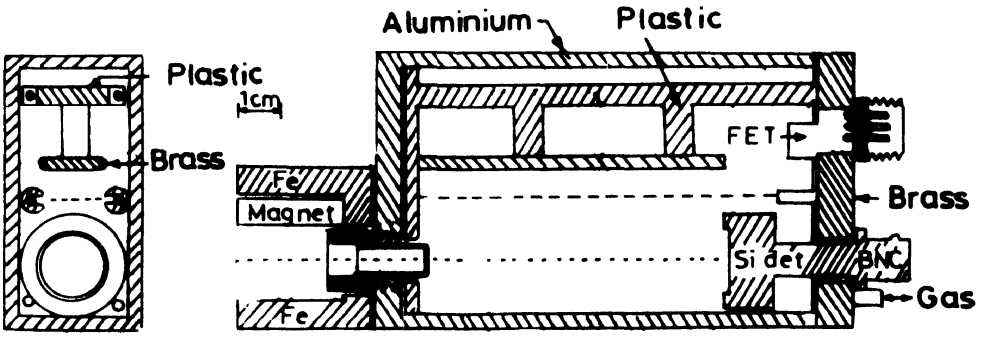

Figure 1. Grided gaseous ionization chamber as ΔE detector with E semiconductor detector forming ΔE–E telescope [9].

~ 1 MeV/nucleon require quite small thickness (~ 10 μm) for desired energy deposition. The surface barrier detector with thickness of < 10 μm are quite fragile and are very expensive. It therefore needs lot of care in its use. Being prone to radiation damage, they have limited life. Detectors with thickness 5 μm are difficult to produce. It is difficult to provide a thin contact layer (dead layer). These thin detectors have excessive capacitance. The type of energies of reaction products encountered in the experiment with the facilities

like 15 UD NSC Pelletron [8] require thin (10 μm) transmission type silicon detector for detection of heavy ions. For such applications, Fowler and Jared [9] suggested the use of gaseous ionization chamber as ΔE detector. A schematic sketch of ΔE grided ionization chamber with semiconductor E detector is shown in Figure 1. It consisted of cathode, anode, Frisch grid, gas inlet, thin entrance window and Si surface barrier detector. The purpose of the Frisch grid is to shield the anode from the effect of movement of charges in main chamber volume. Different algorithms were suggested by different groups [10–12] to analyse the telescope data.

3. Bragg curve spectrometer

Since early eighties, the Bragg curve spectrometer (BCS) has been widely used after it was first designed and tested by Schiessl *et al* [13] and Grauhn *et al* [14]. Conceptually it involves using the information from the Bragg curve for identifying the particle and measuring its energy. The design of detector is such that it measures the Bragg curve with high precision. The total energy is determined from the integral of ionization all over the particle track. Maximum of specific ionization of the heavy ion is the indication of Bragg peak, which is an unambiguous measure of Z of the heavy ion. The advantages of this detector is its insensitiveness to radiation damage, large solid angles high resolution for identifying particles/ions and possibility of Z identification over a large range of energies and particles. Energy resolution of ~0.4% and Z resolution of 1/82 reported by Schiessl *et al* [13] are typical characteristic parameters. Proper pulse shaping with a long and short time constant allow determination of total ionization charge and ionization charge integrated around Bragg maximum, respectively. A schematic view of the BCS is shown in Figure 2. It

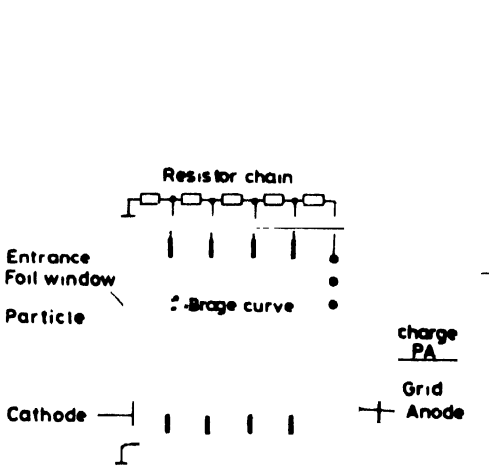

Figure 2. Schematic view of Bragg curve spectrometer.

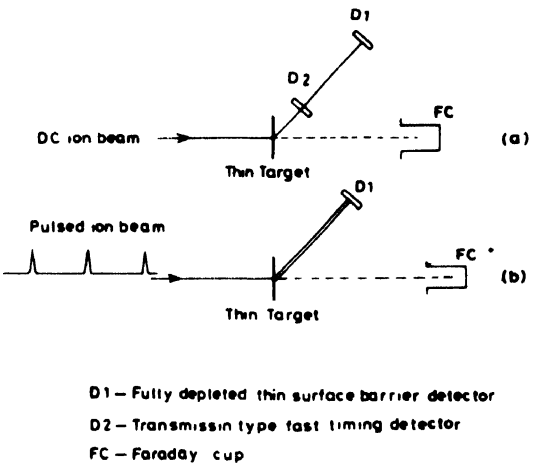

Figure 3. Set up for time of flight experiment.

is a cylindrical ionization chamber with a Frisch grid. The electric field is parallel to the axis. A thin (1 to 2 μm) aluminized mylar foil is provided for the entrance of particles to be detected. The foil also serves as grounded cathode. Uniform potential gradient is provided

by the resistance chain and gaurd rings (closely spaced electrodes at different potential) between the grid and cathode.

4. *M, Z* separation with telescope and TOF

It is seen in the section 2 that the isotopic separation above $Z = 5$ is not possible by ΔE–E telescope. Timing information from detectors is utilized to identify mass of reaction products or ions unambiguously. The time of flight of different masses are measured for a given distance either by using two fast timing detectors or by using the pulsed beam and a fast timing detector as shown in Figure 3. Ions of different mass have different flight times ($= d/v$) where d is flight path and v is velocity of ion given by $1.4\ (E/M)^{1/2}$ where E is the energy of the ions of mass M. If the total energy E_t is known ($E_t = \Delta E + E$), the mass can be determined from the velocity by $M = 2E\,t^2/d^2$. Mass resolution is given by

$$\frac{\Delta M}{M} = \left[\left(\frac{\Delta E}{E}\right)^2 + \left(\frac{2\Delta t}{t}\right)^2 + \left(\frac{2\Delta d}{d}\right)^2\right]^{1/2} \tag{4}$$

The uncertainity in distance measurement Δd is negligible as compared to energy and time uncertainity. It is either due to measurement error or due to different flight paths of ions between the timing detectors which depends on detector solid angle and flight path. This is negligible only when the solid angle is small and flight path is large.

The energy resolution of solid state detectors is typically 5×10^{-3} for light ions ($A = 50$ amu). Very heavy ions and large solid angle requirements necessitate the use of gaseous detectors which have resolution of the order of 1% [15].

The other factors which need to be looked into are the energy loss [16], energy straggling [17] and angular straggling [18]. Energy straggling deteriorates the energy resolution. Straggling increases with the Z, thickness x of the material through which ion passes. It is given by rough approximation as $E = x^{1/2}Z$.

Heusch *et al* [19] showed the effect of angular straggling on the yield measurement. As indicated in Figure 4, the heavier and lower velocity ions are lost considerably (up to 30% for ^{20}Ne of 5 MeV) due to angular straggling as predicted by collision theory of Meyer [20]. Therefore one has to take into account these losses or one has to carry out an efficiency calibration with different targets of known thickness. The efficiency loss is dependent on the parameters of TOF set up such as distance, carbon foil thickness and solid angle of detector as well as on the incident ion mass and energy.

The flight path in the experiment is to be chosen in such a way that the difference in flight time in the ions of interest is more than the time resolution of the system. In the case of pulsed beam based TOF, the pulsed beam repetition rate should be larger than the flight time of heaviest ion under study.

Fast timing detectors mostly employed for TOF are microchananel plate [21,22], fully depleted surface barrier detectors (overbiased) [23], plastic scintillator [24], parallel plate avalanche counters [25] *etc*.

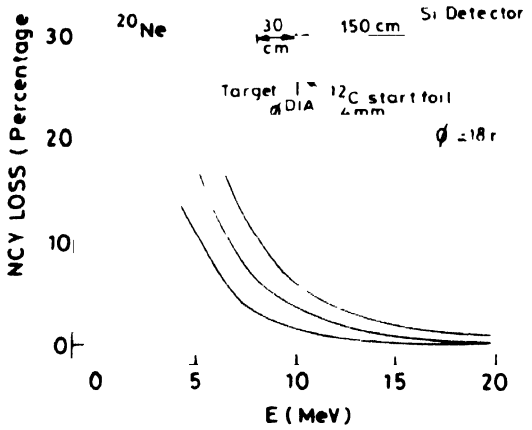

Figure 4. Loss of efficiency due to angular straggling for different ions [18]

4.1. TOF with pulsed beam

Pulsed beam is a short burst of ions at regular interval produced by buncher. The principle of operation of buncher is that the energy modulation of accelerated ion beam is done by applying radio frequency (RF) voltage across two gaps separated by a distance d which is decided by the frequency of RF. In TOF experiment with pulsed beam the stop signal is taken by RF of the pulsing system.

Mass resolution in the experiment will depend on time resolution of the pulsed beam as well as the detection system. The best resolution of the buncher is ~ 100 ps for post acceleration bunchers, which use a quarter wave resonator cavity [26], spherical cavity [27] *etc*. as the bunching device. However the bunchers in pre-acceleration region like the one existing at NSC [28] and TIFR [29] have the time resolution of 1 to 3 ns. Typically, time resolution of 3 ns will result in mass resolution M/M = 0.085 for ions with energy ~ 1 MeV/n and a flight path of 70 cm available in general purpose scattering chamber [30].

4.1.1. Discrimination by TOF

Neutron detection is carried out by liquid scintillator mounted on photomultiplier tube, which is also sensitive to γ-rays and it becomes difficult to know whether the detector signal is from neutrons or from γ-rays. However these two radiations, despite their almost similar energies, can be distinguished by TOF due to their different velocities of ~ 30 cm/ns and ~ 1.4 $E^{1/2}$ cm/ns for γ-rays and neutrons respectively, where E is neutron energy. Flight

path is chosen in such a way that flight time difference of γ-rays and neutron is much more than *fwhm* of the pulsed beam. Spectrum in Figure 5 indicates a small broader peak which is due to neutron and it could be separated from the sharp γ-ray peak due to their difference in flight times in a flight path of 1 m.

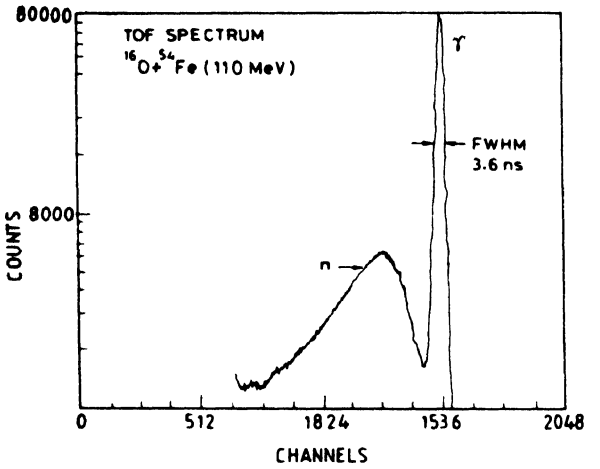

Figure 5. A time of flight spectrum observed with BC 501 liquid scintillator which ^{16}O ions of 110 MeV bombarded ^{54}Fe target

5. Pulse shape analysis

Neutron detection is normally studied through discrimination by TOF. However, high energy neutrons tail often mix with the γ-ray peak. Pulse shape analysis is normally carried out to separate the high energy neutrons from γ-rays.

Pulse shape discrimination analysis technique was originally developed [31] for n–γ separation. The basis of technique is that the fall time of output signals produced by n and γ in the organic scintillator have different decay times. Many developments took place in this field which are summarised by Brooks [32] and references therein.

An improvement in the technique was carried out by Sperr *et al* [33], in which the anode pulse a of photomultiplier tube is integrated and differentiated so that the zero crossing point of the output pulse is determined by the fall time of input pulse. The shaped signal is then fed to high gain limiting amplifier, which enhances the separation of zero crossing points. Later a commercial NIM module was made by CANBERRA exploiting this technique.

6. Summary

Identification of the ions or products in the exit channel of a heavy ion reaction is described briefly. ΔE–E telescope detector, the need for gaseous ionization chamber as ΔE detector and the Bragg curve spectrometer are discussed for Z separation of ions. Mass

identification by TOF is described. n–γ discrimination by TOF and pulse shape analysis are also discussed.

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